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Scaled experiments for a simple deformable structure under liquid slug impact

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ABSTRACT

For the assessment of similarity laws and the identification of size-scale effects a series of fluid-structure impact experiments in three different scales 1:2.5:10 were performed: A drop weight accelerates a water slug which impinges on a rigid target plate connected by deformable bending joints (minimum diameter 10, 4, 1 mm) to a rigid support. The results for two different joint materials (ferritic steel St 37, austenitic steel X 5 CrNi 18 9) and different impact speeds are presented and compared with calculations. The scale influence on the permanent target plate rotation is moderate for St 37 and can be interpreted by its strain rate sensitivity. However, a striking effect is found for the austenitic steel with the tendency that smaller specimens suffer much less rotation, an effect which is beyond the strain rate influence. Several causes are discussed and future work is indicated.

1. INTRODUCTION

The in-vessel steam explosion in a Pressurized Water Reactor is an accident scenario under investigation. A theoretical analysis of the resulting corium slug impact appears to be very difficult. Therefore, a scaled down model experiment (BERDA experiment, scale 1:10, [1]) with an alternative energy source is performed. Clearly, the design of this experiment and the transfer of the experimental results to reactor dimensions using scale factors requires appropriate similarity laws.

This scenario primarily involves the following phenomena: Transient motion of a compressible, viscous liquid, dynamic deformations of elastic-plastic or viscoplastic structures as well as their interaction during and after impact; for sufficiently large energy releases also failure and fracture of structures may occur.

Restricting the attention to processes without failure, it is noted that classical elasticity, rate independent plasticity as well as inviscid compressible fluids do not involve an internal length scale associated with the material response. Because of this scale independence the related similarity laws can, in principle, be satisfied if replica models (same material and temperature for model and prototype) are used and if the characteristic velocities (e.g. impact velocity) are the same. However, non-similarity and thus size effects may occur for replica models if the rate dependence of the flow stress and the viscosity of the fluid have a significant influence, not to mention other possible effects. Therefore, it is required to perform fluid-structure impact experiments with replica models of several different scales.

For structures suffering elastic-plastic deformations without fracture, the validity of the elementary geometrical scaling laws have been studied experimentally before.

Baker [2, 3] investigated the transient elastic-plastic bending of scaled cantilever beams made from rate insensitive aluminium sheets subjected to blast loading in air using scaled explosive charges. The scaling was 1:2:4. At first sight the scaled permanent tip deflections appear to follow the scaling laws. However, a more detailed analysis of the experimental data shows [4] a systematic scale influence when the scaled tip deflections of the beams are below 5/10 of the original beam length: The smaller specimens show significantly larger scaled deflections than the larger specimens. The possible variability of the mechanical properties was not discussed and thus this and other plausible explanations of the scale influence are lacking.

In the frame of safety analyses for hypothetical core disruptive accidents of sodium cooled breeder reactors a few systematic scaled model tests were done by firing an explosive charge in water filled models of reactor vessels [5, 6]. Takei et al. [5] performed complex model tests with a scale ratio of only 2:1. The materials of these test vessels were all austenitic steel SUS 304. These tests allow to asses a possible size effect on the vessel deformations. Differences were found in the maximum strains. Thus, the two times larger set-up without upper internals suffered an almost 30 % larger maximum hoop strain. Whether this difference is indeed caused by a systematic scale effect is uncertain since the tests were not repeated and the variability of the flow stress of the sheet metals were not indicated.

Similar studies were done by Florence et al. [6] with simplified scale models of a fast test reactor. The scale factor between the models was 3:1. Unfortunately, the scaling ratio for the vessel wall thickness was more than 4:1 instead of 3:1 because of restricted availability of commercial stainless steel sheets. Therefore, conclusions about similarity or size effects of the vessel wall deformation are severely hampered.

These examples underline the need for further experimental studies which cover a larger range of scales and which allow the determination of the scatter of repeat experiments.

2. SOME RESULTS FROM SIMILARITY THEORY

Starting from the balance and constitutive equations and from initial and boundary conditions for an elastic-viscoplastic solid (Perzyna-type overstress model with strain hardening) and a compressible Newtonian fluid, the similarity laws are derived by transforming the governing equations into a dimensionless form [4, 7]. It should be noted here that the derived similarity laws are valid only as far as the underlying physical theory is valid and appropriate. Therefore, the identification of the relevant physical processes is most important.

For an inviscid, compressible fluid and elastic rate independent plastic solid similarity requires, among others, that Cauchy's number for the fluid and the non-dimensional stress-strain curves of the solids are the same for the small scale model and the large scale situation. This is trivially achieved if replica models (same material at the same temperature) are used and if the reference velocities (e.g. impact velocity) are the same. However, if viscous effects (fluid viscosity and visco-plasticity) are present, the Reynolds* number of the fluid and also the viscoplastic Reynolds* number of the solid must be the same for the small and the large scale situation. This cannot be achieved in a replica model. Thus, in the solid a size-scale effect is introduced since the strain rate in the small model is λ-times** greater than in the larger one and this usually implies a larger resistance against plastic flow in the small scale model. These and other scale effects are investigated in the test series FLIPPER (<u>Fl</u>uid <u>Imp</u>act <u>Exper</u>iment).

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* This dimensionless number is equivalent to a ratio "characteristic geometric length / internal material length scale" [7].

** Scale factor $\lambda = \ell p/\ell m$; ℓp & ℓm characteristic length of prototype and model.

3. THE EXPERIMENTS FLIPPER

Fig. 1 shows a schematic sketch of the experimental set-up FLIPPER. A drop weight is used to accelerate water contained in a reservoir which is closed at the bottom by a thin aluminium diaphragm and at the top by a floating cover. In the course of the experiment the water cover is retained in the reservoir and the drop weight is decelerated by a shock absorbing material. Below the container there is a rectangular target plate made from brass which is connected to the stiff supporting structure by two bending joints (Fig. 2). After the impact all the plastic deformation is concentrated in these joints.

The primary measurement is the permanent rotation of the target plate measured after the experiment. However, additional observations and measurements were done concerning the speed of the drop weight using laser beams and the deformation and rupture of the diaphragm and the flow of water using a high speed camera.

The experiments were performed in three similar set-ups constructed according to the scales $\lambda = 1$, 2.5 and 10. The scaling involves the target plate and the bending joints, the water reservoir, the drop weight and the supporting structure. The relevant geometrical data are given in Tables 1 and 2. In all tests water was used as the impacting fluid.

Aside from the scale factor λ, further test parameters were the drop height of the drop weight which determines the impact velocity of the water slug and the material for the bending joints including:

- the structural steel St 37; its mechanical behavior in a tensile test is characterized by an upper and lower yield strength and by a pronounced strain rate sensitivity at large strain rates:
- the stainless steel X 5 CrNi 18 9 which is moderately rate sensitive but shows a pronounced strain hardening;
- the aluminium alloy AlZnMgCu 1.5 which is rather strain rate insensitive (because of limited space these data are not discussed here).

All bending joints were fabricated from the central portion of circular rods.

4. EXPERIMENTAL RESULTS

4.1 Ferritic Steel St 37

The experimental results - permanent rotation of the target plates versus scale of the test specimen - for the structural steel St 37 are shown in Fig. 3 and 4. Three series of nominally identical tests were performed:

- Group I (marked by ○): All bending joint specimens were fabricated from a single rod (16 mm diameter); tests only for smallest and medium size; drop height 2m
- Group II (marked by ◇): All specimens were fabricated from a single rod (16 mm diameter) but different batch than Group I; increased fabrication precision to reduce tolerances; tests only for smallest and medium size; drop height 2 m (also 1.6 and 2.4 m)
- Group III (marked by Δ): All specimens fabricated from several rods (30 mm diameter) because of increased number of tests; tests for all three scales; drop height 2 m (also 1.5 and 3 m)

If similarity laws for non-viscous replica models were obeyed, the permanent rotations of the target plate should be the same for all scales. Nevertheless, in the experiments a scale effect is expected because of the strain rate sensitivity of the steel and possibly also due to the viscosity of the water.

Fig. 3 shows the scatter of the individual tests together with the mean values and their 90 %-confidence intervals. Except for the medium size specimens of Group III a monotonous increase of the permanent rotation is observed when the size is increased. Qualitatively, this is in accordance with the strain rate sensitivity of the flow stress of St 37. A quantitative assessment is discussed in section 5.

In order to explain the depression of the medium size experiments of Group III, a phenomenon not observed for Group I and II experiments, additional scaled static bending experiments were done with used Group III-specimens of all sizes [4]. The same trend was observed. This suggests that the depression is a material property related phenomenon: The various Group III specimens were fabricated from different rods which probably came from different batches.

The influence of the drop height on the mean values of the permanent rotation of Group II and Group III specimens is shown in Fig. 4 where the specimen size is the parameter. If similarity would prevail, then the curves of each group should collapse into one. It is noteworthy that there is an almost linear relation between the permanent rotation and the drop height with an approximately scale independent slope. These observations may partly be interpreted using energetic arguments [4]: The scale independent slope is an indication of the scale invariance of the energy partition between the available kinetic impact energy and the energy dissipated in the bending joints.

Extrapolating the almost linear graphs towards the abzissa yields a minimum drop height which is required to produce a permanent rotation. It is noteworthy that the scale dependence of these linear graphs is almost completely contained in the minimum drop height and this increases with a decrease in the size of the specimens. Since the minimum drop height is related to the initial yield moment of the joints, this trend is qualitatively in accordance with the strain rate influence on the yield stress. Finally, it is noted that the depression of the permanent rotation of the medium size Group III specimens is also observed for the other drop heights (espec. 3 m).

To enhance the influence of viscous fluid forces additional scaled fluid impact tests were performed with perforated target plates , their mechanical properties adjusted [4], and using a height of 3.8 m. Group III bending joint specimens were used. Compared to the experiments with unperforated target plates with 1.5 m drop height, which have a comparable permanent rotation, the relative decrease of the permanent rotation from the largest to the smallest specimen is about 31 % instead of 37 %. This is a rather moderate difference. One concludes that fluid viscosity is of minor importance compared to strain rate sensitivity.

4.2 Austenitic Steel X 5 CrNi 18 9

Several test series were performed with bending joints all made from a single rod (30 mm diameter) of stainless steel X 5 CrNi 18 9. The different specimens were taken from the rod centre at various positions along the rod to average variations of material properties along the rod length. Also Vickers hardness tests across rod diameters were performed to assess the uniformity. The hardness was rather constant but a slight increase of 10 % was observed close to the rod centre [4]. In addition quasistatic and dynamic tensile tests (6 mm diameter specimen) were done which showed a moderate rate influence [4].

A first series of tests was performed for all three sizes with a drop height of 1.9 m (marked by triangles in Fig. 5). A significant size effect is observed: The permanent rotation of the large size specimen (10 mm diameter) is more than three times larger than the smallest specimen (1 mm diameter). To account for the influence of cold working due to the turning of the joint specimens, two different annealing processes (650 and 700 °C with different annealing times adjusted to the size of the specimens [4]) were applied to two sets of virgin specimens. Drop tests with these specimens showed a significant increase of the permanent rotation for the smallest specimen (Fig. 5). However, the two other size specimens are only moderately affected. This influence is to be expected since the cold working is restricted to a finite almost constant depth at the specimen surface.

Nevertheless, a significant size effect remains which is non-monotonous since the medium size specimens suffered the smallest permanent rotations.

5. CALCULATIONS WITH A STRUCTURAL DYNAMICS MODEL

The purpose of the application of a structural mechanics model is twofold: To assess

- whether the viscoplasticity of the bending joint materials is the primary cause for the observed scale dependence of the permanent target plate rotation
- and whether geometric tolerances or variations in the transient loading of the plate are sufficient to explain the scatter of nominal identical experiments.

The details of the computational model are described in ref. [4]. Only its main features are given here: The target plate is considered to be rigid, the flexible bending joints with their variable cross-section are represented by an elastic-viscoplastic beam model with a uniform ersatz-cross-section and -length, the viscoplasticitiy is described by a Perzyna-type overstress constitutive equation with strain hardening which was fitted to static and dynamic tensile tests of the relevant steels. The hydrodynamic force on the plate is based on force histories measured at an unmoveable target plate of medium size for a drop height of 2 m; measurements were available for ten nominally identical tests which gave a variation of ±7 % of the final impulse. For the dynamic model, however, the relative motion between the fluid and the rotating plate was accounted for in the equation of motion for the plate. For each specimen size the ten measured force histories, appropriately scaled, were used in the calculations to simulate variances in the loading but also a ±2 % diameter variation of the ersatz-cross-section of the joint was superposed.

The calculational results for St 37 with a drop height of 2 m are included in Fig. 3. It is seen that their scatter is considerable and quite comparable to the experimental scatter. Thus, it can be concluded that the moderate variability in the hydrodynamic force yields an considerable scatter in the permanent rotation. This enlargement is due to the non-linearity of the strain hardening model.

The calculated mean values of the plate rotation are consistently above the measured mean values; this is also found for the other drop heights [4]. It is likely due to the simplicity of the theoretical model. However, the relative size effect due to the viscoplasticity found in the calculations, i.e. the change of the rotation with the size, is approximately the same as found in the experiments; of course, the medium size Group III-experiments are an exception. Thus, it is concluded that the experimentally found size effect is primarily due to the strain rate sensitivity of the bending joint material St 37.

Corresponding calculations were performed for the experiments with austenitic steel X 5 CrNi 18 9. The reduction in drop height (1.9 instead of 2 m) is accounted for in the hydrodynamic force input [4]. The comparison of the calculational results with the experimental data for the heat treated steel shows an excellent agreement for the largest size specimens but a gross overestimation of the medium and small size specimens (Fig. 5). Also the relative size effect seen in the calculations, which is only due to the viscoplasticity, changes monotonuously with the size and is rather moderate. Consequently, the significant size effect observed for the austenitic steel cannot be explained by the strain rate sensitivity of this material.

6. DISCUSSION AND CONCLUSION

The experimental results for the ferritic steel St 37 show a moderate size effect over a scale factor of 10. Comparison with calculations suggests that this is primarily due to the strain rate sensitivity of the bending joint material. This result then implies that the purely hydrodynamic processes scale according to the elementary similarity rules; thus fluid viscosity and surface tension are not important here. This interpretation is also supported by the results obtained for the perforated target plates where enhanced viscous fluid forces are present. The depression observed for the medium size Group III specimens, not found for Group I & II specimens, is likely to be caused by a difference in the material property of this series of specimen sizes. It underlines the importance of a careful control to assure that the raw material is from the same heat and is produced in the same way.

The scatter observed in this type of experiments is reproduced by the calculations: Moderate random variances in the fluid slug properties are enhanced by the nonlinear material response of the structure. This effect is of particular concern when one is restricted to perform only a single or a few scaled down model experiments and extrapolation to a large size situation is required.

The experimental results of the scaled fluid-structure impact experiments with bending joints made from the austenitic steel X 5 CrNi 18 9 revealed a significant size dependence with the tendency that smaller specimens appear to have a larger resistance against plastic flow. Neither this trend nor the observed depression of the heat treated medium size specimens can be explained in any way by strain rate sensitivity of the austenitic steel. There is also no indication of a deformation mode transition due to partial cracking of the larger specimens.

Pseudo effects like the variability of the mechanical properties in the raw material or due to the turning of the joint specimens can be excluded since special care was taken for these influences. Also a machine effect, especially with respect to the observed depression, appears not to be likely since the three set-ups were quite similar.

Of course, there remains the possibility that an inherent material property causes this scale dependence. In fact there exists some experimental evidence that the properties of plastic flow are scale dependent especially when the strain distribution is non-uniform [7]: Morrison [8] and Richards [9] performed scaled torsion and pure bending experiments using mild steel specimens; Fleck et al. [10] accomplished scaled torsion experiments on very thin pure copper wires. In all these cases the experiments showed that the smaller specimens have a larger resistance against plastic flow, whereas under simple tension (homogeneous strain distribution) no or only a very moderate scale influence was found; further, this effect dies away monotonically with the increase of the absolute size.

These observations suggest to perform additional, at least quasistatic bending experiments with scaled specimens produced from the same austenitic steel rod as used for the FLIPPER test series.

Finally, it is noted that in constitutive modelling various concepts are under discussion which involve an internal material length scale: Extension of constitutive models by non-local (integral) terms (e.g. Bazant et al. [11]) or by higher order spatial gradients (e.g. Aifantis [12]) or the use of polar media models (e.g. Fleck et al. [10]). It remains to be shown whether such models are capable to describe observed size effects in technological important materials.

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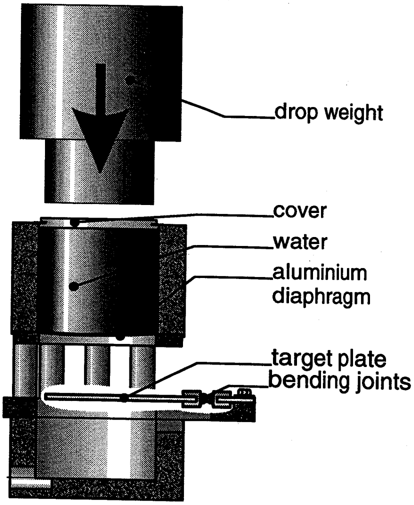

Figure 1: FLIPPER - test principle

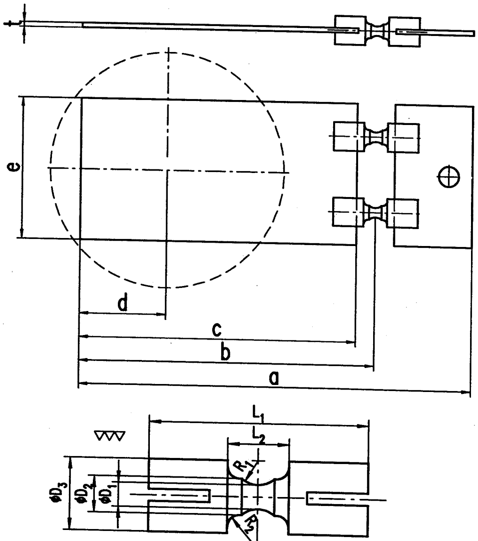

Figure 2: Target plate and bending joints

scale λ	1	2.5	10
mass of drop weight [kg]	240	15.4	0.24
max. drop height [m]	3.8	3.8	3.8
inner diameter of reservoir [mm]	250	100	25
inner diameter of flange [mm]	245	98	24.5
eff. height of reservoir [mm]	220	88	22
distance target plate - diaphragm [mm]	135	54	13.5
thickness of diaphragm [μm]	50	20	8

Table 1: Geometrical data of the FLIPPER set-ups

λ	1	2.5	10
a	417.5	167	41.75
b	315	126	31.5
c	295	118	29.5
d	92.5	37	9.25
e	150	60	15
t	5	2	0.5

λ	1	2.5	10
D_1	10	4	1
D_2	15	6	1.5
D_3	30	12	3
R_1	10	4	1
R_2	5	2	0.5
L_1	90	36	9
L_2	25	10	2.5

Table 2: Geometrical data for the target plate and the bending joints in [mm] according to Figure 2

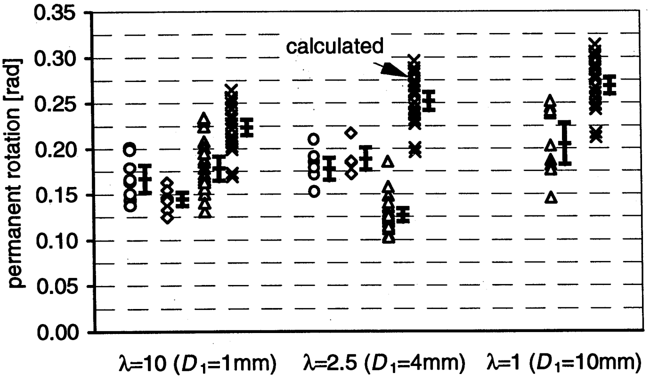

Figure 3: Target plate rotation versus scale; bending joints St37, drop height 2m (for symbols refer to the text)

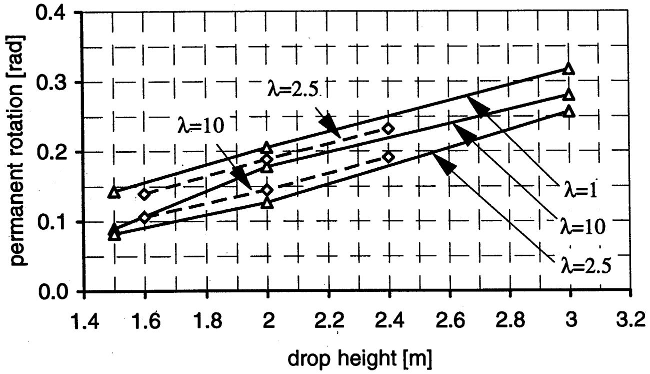

Figure 4: Target plate rotation versus drop height; scale factor λ is parameter, bending joints St37 (for symbols refer to the text)

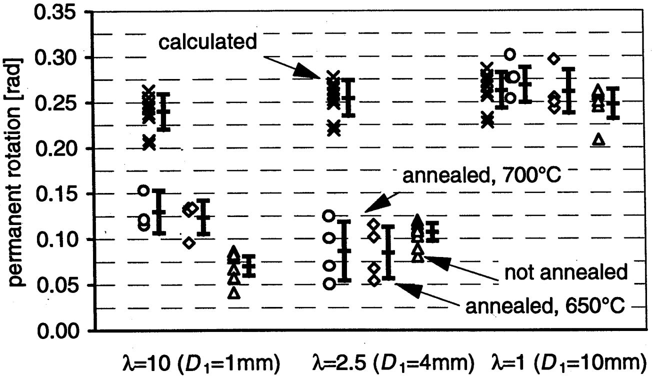

Figure 5: Target plate rotation versus scale; bending joints X5 CrNi 18 9